Lidar characterizations of atmospheric aerosols and clouds

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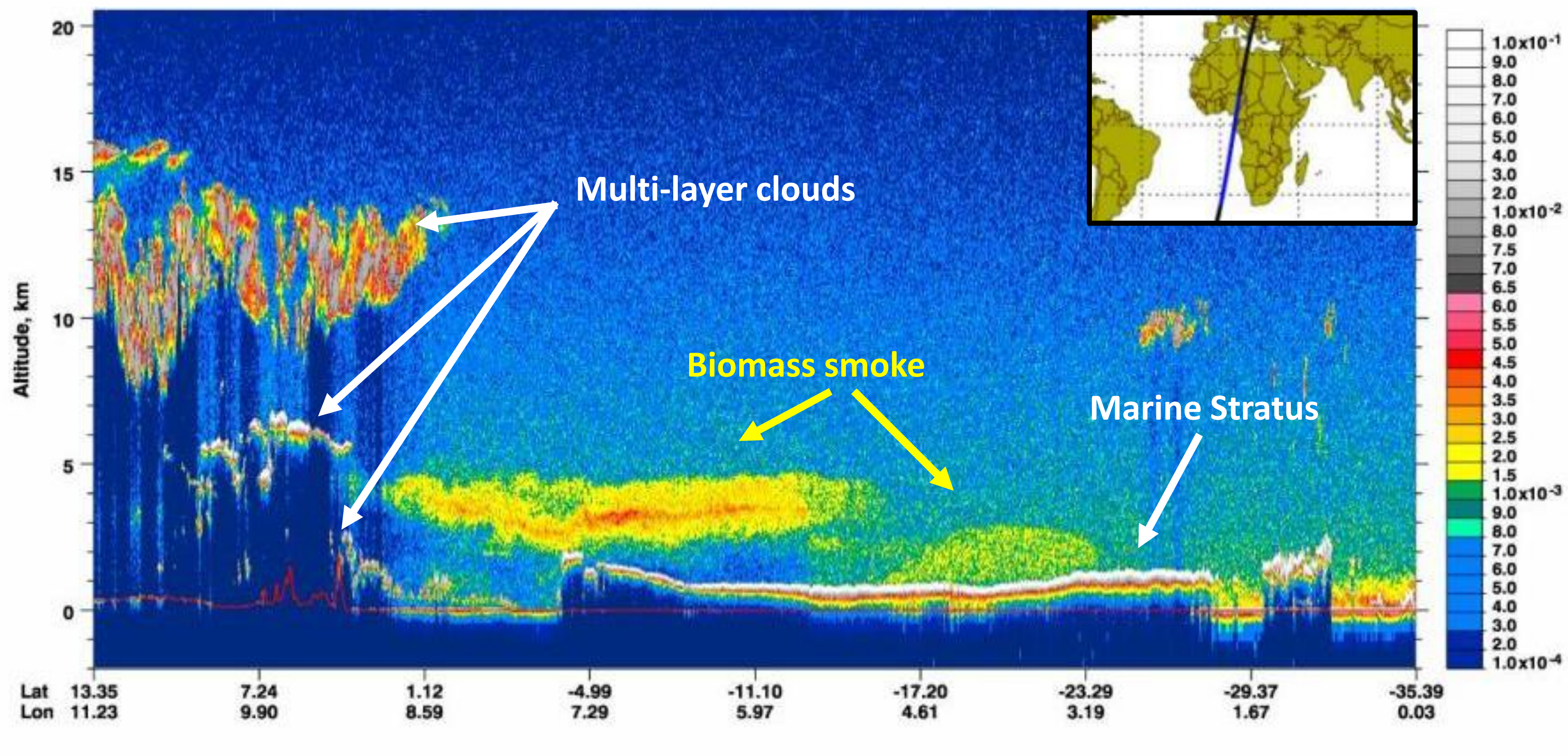
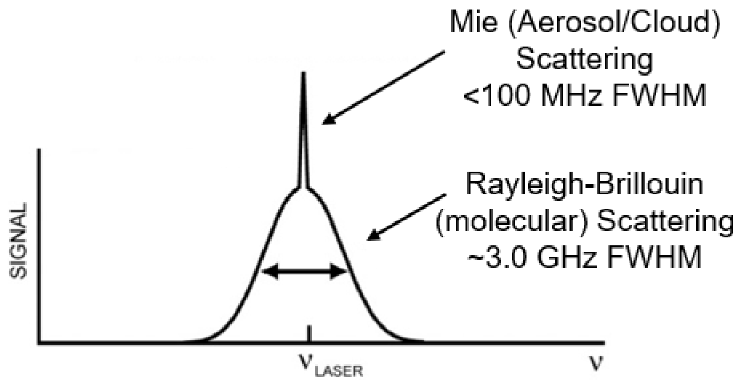
NASA Langley Research Center, Hampton VA

CALIPSO observations of smoke over low clouds

CALIPSO clearly demonstrated the necessity of vertically-resolved measurements of clouds and aerosols for climate, weather, and air quality applications.

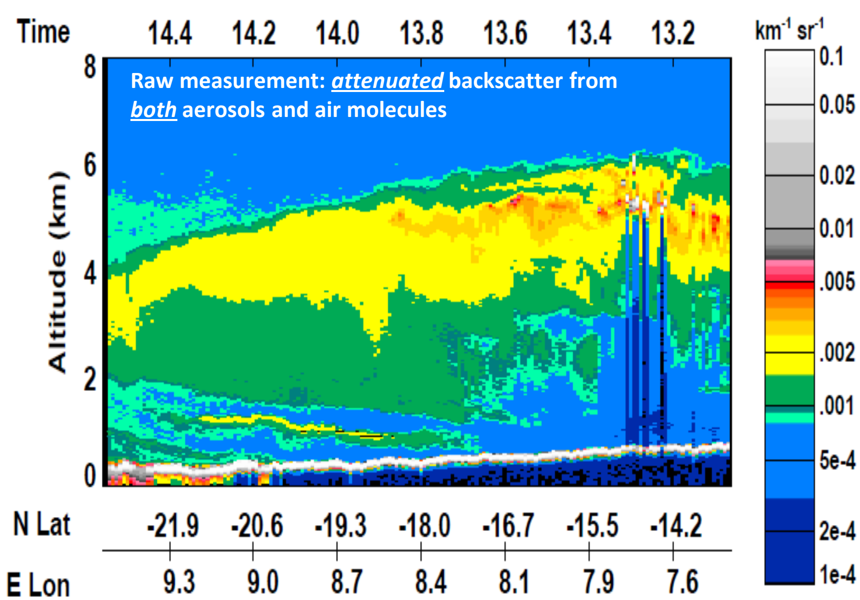


Elastic Backscatter Lidar Measurements



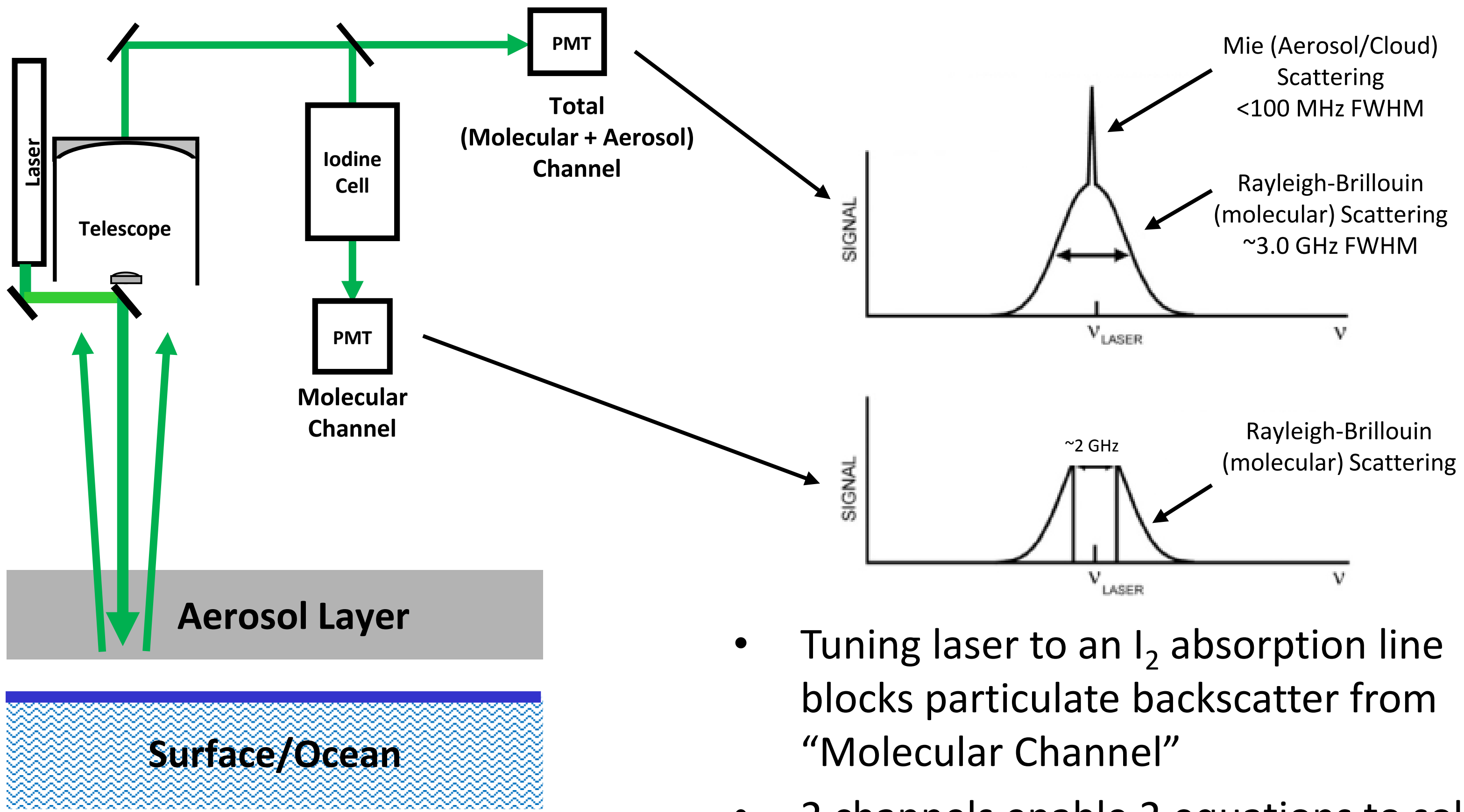
2 unknowns

$$P_a(r) = \frac{C}{r^2}\underbrace{[\beta_m(r) + \beta_a(r)]\exp\left\{-2\int_0^x [\alpha_m(r') + \alpha_a(r')]dr'\right\}}_{\textit{attenuated}\text{ backscatter}}$$



- **Problem:**
  - Lidars measure the ***attenuated*** backscatter coefficient
  - What we actually want is
    - The ***true*** aerosol backscatter coefficient
    - And the aerosol extinction coefficient
  - To get these, we must somehow correct for extinction as the retrieval proceeds downward through the profile
    - This correction can have significant errors

High Spectral Resolution Lidar (HSRL) Technique



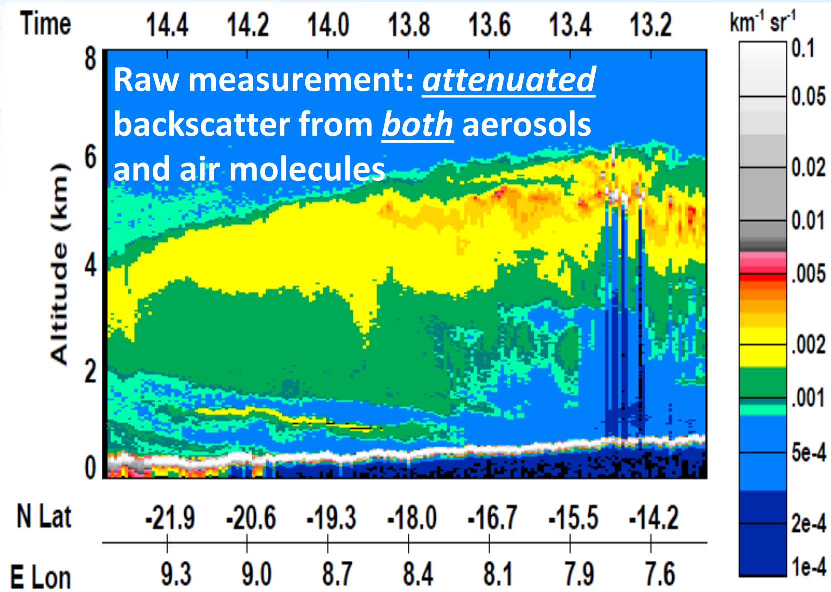
- Tuning laser to an I_2 absorption line blocks particulate backscatter from "Molecular Channel"
- 2 channels enable 2 equations to solve for 2 unknowns: aerosol backscatter and extinction

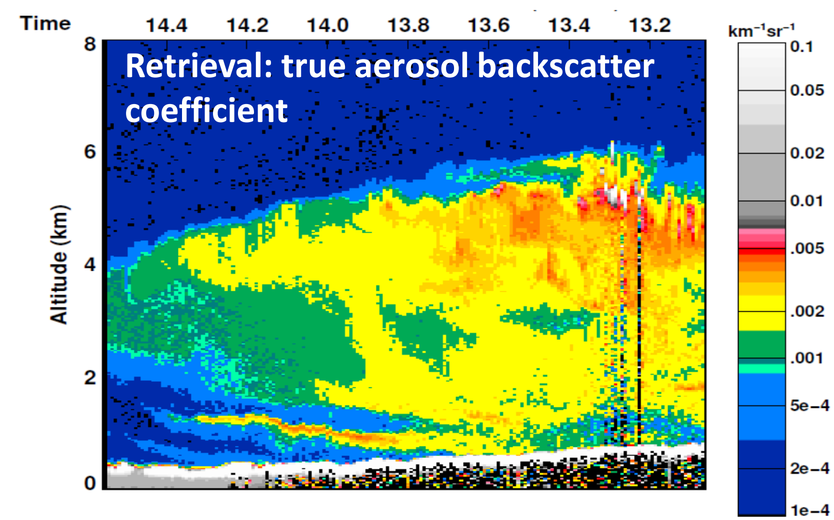
Why use HSRL for aerosol research?

2 unknowns

2 equations
$$\begin{cases} P_a(r) = \dfrac{C}{r^2}[\beta_m(r) + \beta_a(r)]\exp\left\{-2\int_0^x [\alpha_m(r') + \alpha_a(r')]dr'\right\} \\ P_m(r) = \dfrac{C}{r^2}[\beta_m(r)]\exp\left\{-2\int_0^x [\alpha_m(r') + \alpha_a(r')]dr'\right\} \end{cases}$$

- Backscatter coefficient
  - Direct measure of backscatter, rather than attenuated
  - Accurate at all altitudes; errors do not accumulate with range
- Independent measure of extinction
  - No need for inferred/modeled lidar ratio or external constraint
  - Molecular channel also provides direct measure of AOT
- Highly accurate particulate depolarization
  - Separating particulate and molecular parts requires accurate backscatter
- Vertically resolved aerosol type information
  - Lidar ratio gives the most information about aerosol composition for non-dust aerosol





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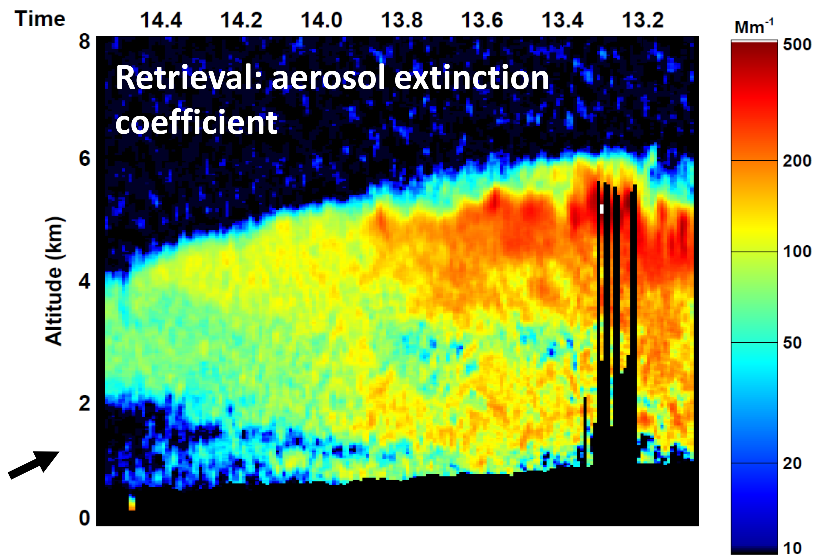
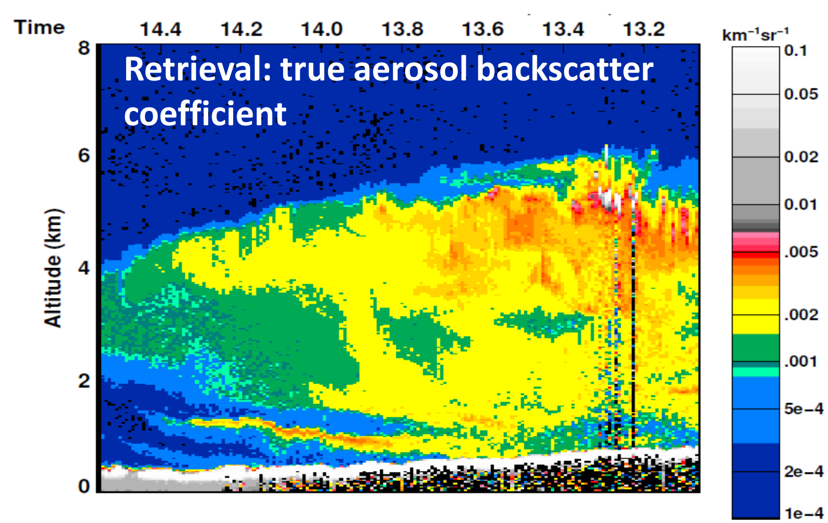
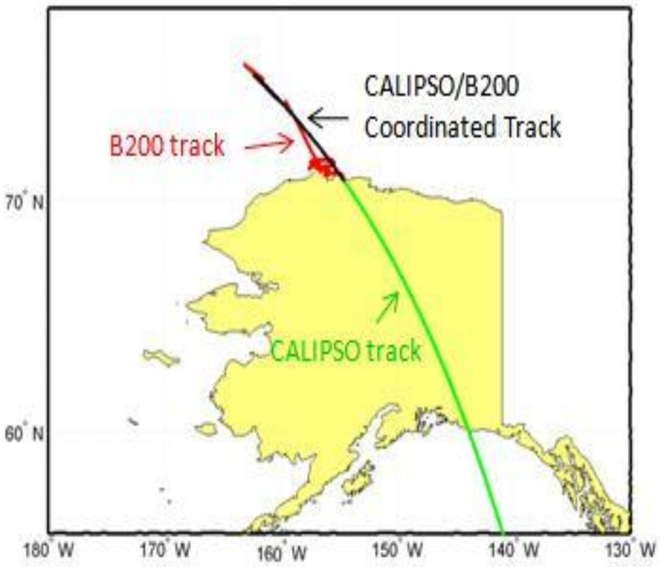
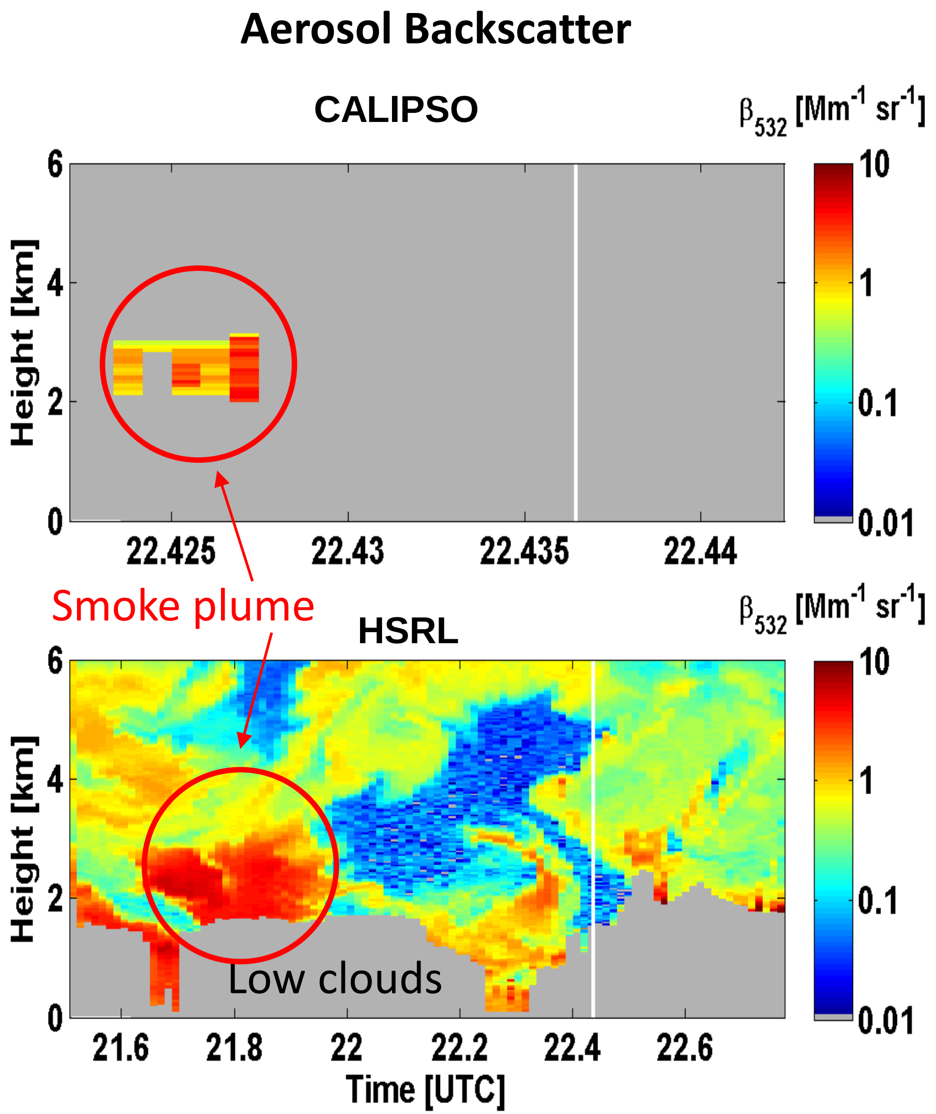




CALIPSO misses much of the Arctic Aerosol

April 19, 2008 (ARCTAS)



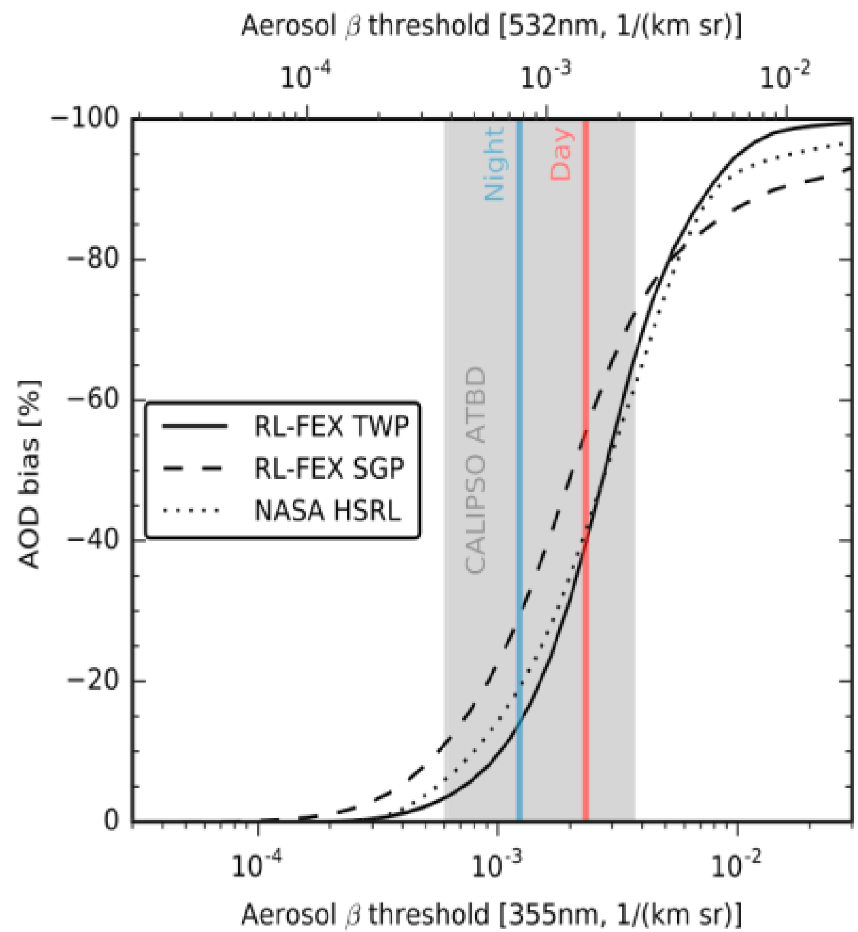


- **CALIPSO sees major aerosol transport events (dust, smoke)**
- **CALIPSO misses background Arctic aerosols below detection threshold**

Rogers et al., 2014, AMT

CALIPSO does not detect all radiatively significant aerosol

- CALIPSO aerosol detection sensitivity was compared to ground-based DOE ARM Raman lidars and LaRC airborne HSRL data
- CALIPSO underestimates global-mean AOD, and therefore shortwave aerosol direct radiative effect, by about 22-47% (38-54%) in cloud-free (transparent profiles) (Thorsen and Fu, 2015)
  - Similar sensitivities as other studies (Rogers et al., 2014)
  - Undetected AOT of 0.031±0.052 (Kim et al; 2016)
- CALIPSO's performance is as expected (consistent with ATBD)



Thorsen et al., 2017

HSRL-DIAL group developed and fields three (soon to be four) airborne lidars that employ HSRL technique

HSRL-1
Aerosols, clouds, ocean
2004 – Present

HSRL-2
Aerosols, clouds, ozone, ocean
2012 - Present

UV DIAL/HSRL
O3 and aerosols
1983 - Present

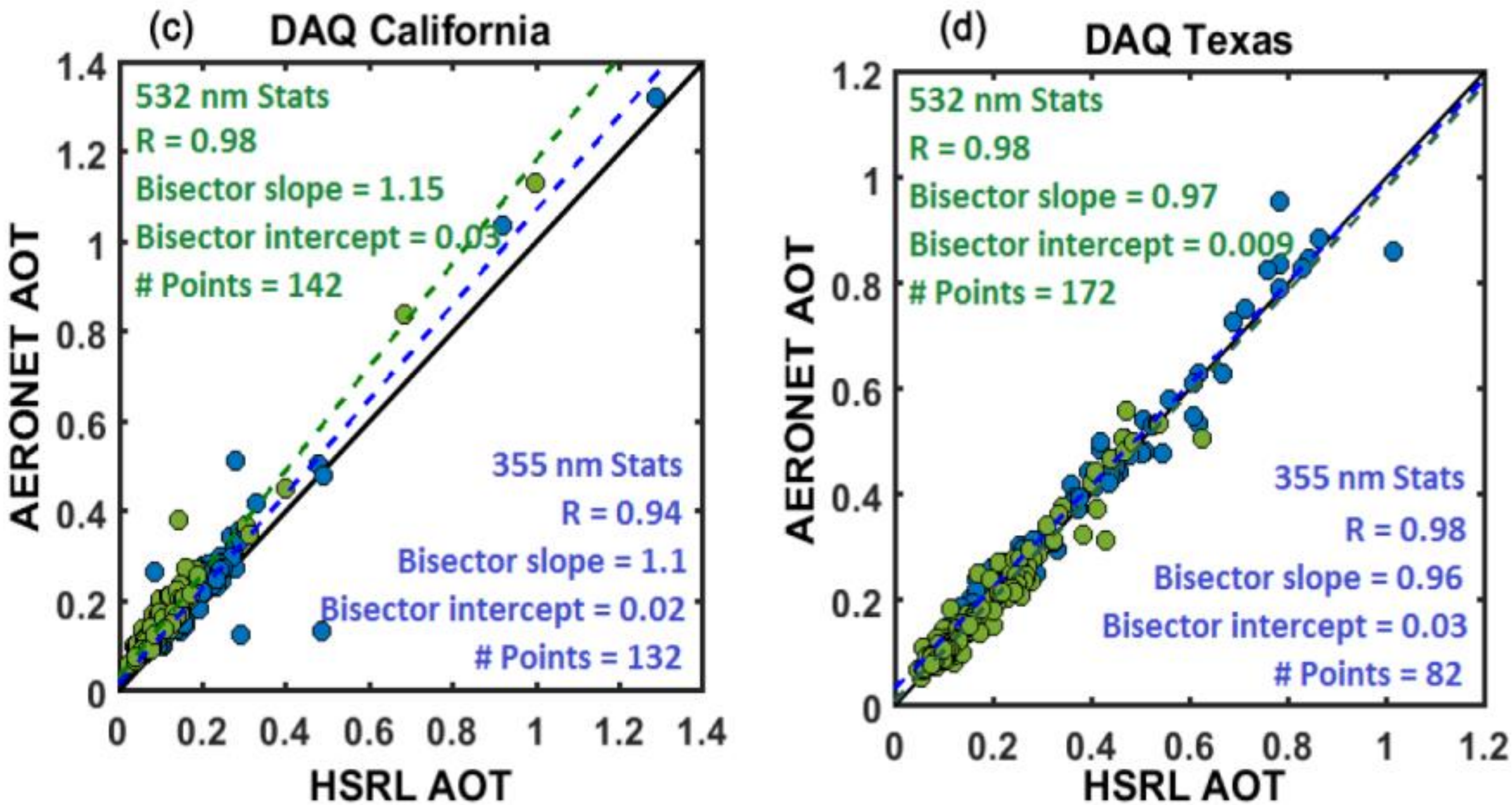
Prototype for the spaceborne lidar on the ACE Decadal Survey mission

Coming soon: HALO
Methane, water vapor, aerosols, clouds, ocean
2018 -

Technology development and demonstration for future space methane and water vapor lidar

Comparisons with AERONET provide high confidence in HSRL-2 extinction product

HSRL 0-7 km layer AOD values compare well with column AOD (355 and 532 nm) values from AERONET "DRAGON" stations when HSRL was within 2.5 km of site and 10 minutes from measurement

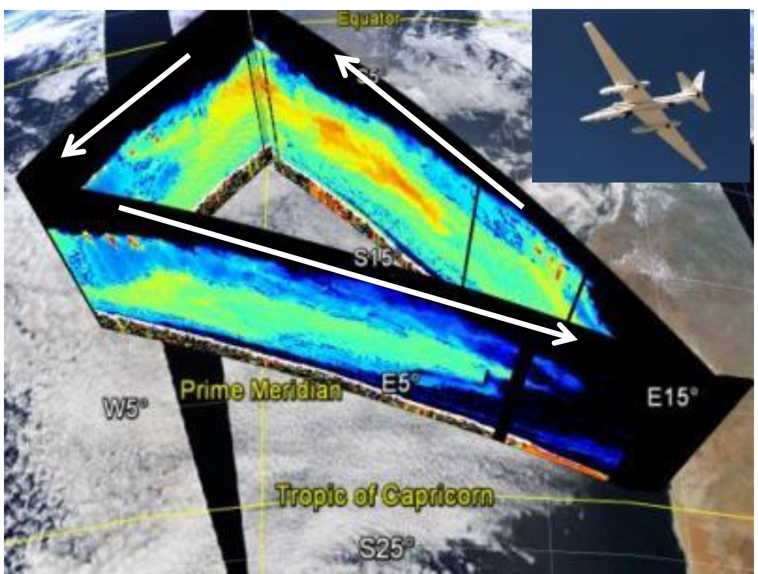


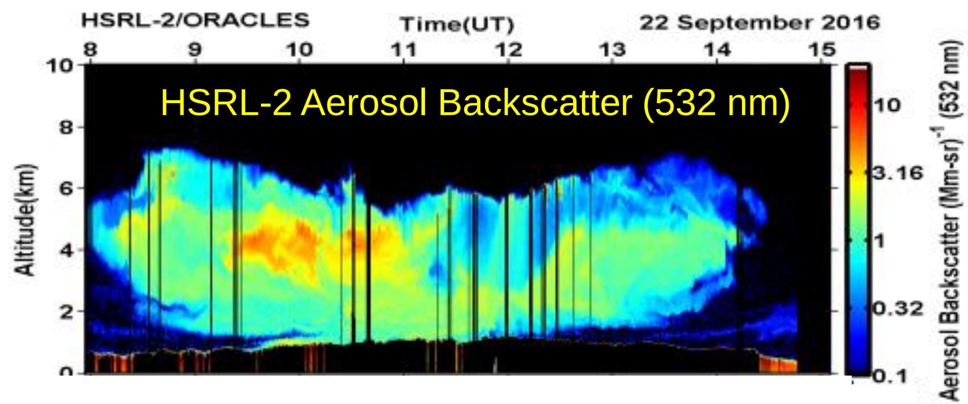
Sawamura et al., 2017, ACP

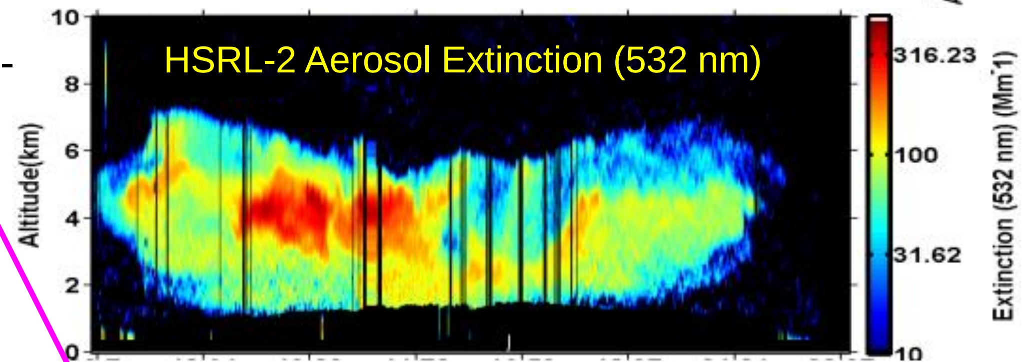
Airborne NASA LaRC HSRL-2 measuring smoke distribution and properties for model evaluation during ORACLES

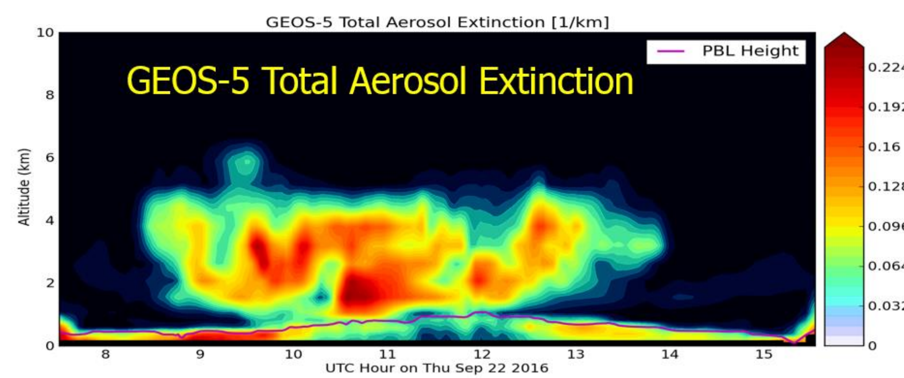
- ORACLES Earth Venture Suborbital mission
- Target: Extensive biomass smoke plume over persistent stratus cloud deck off the west coast of Africa
  - Smoke has significant radiative effect: localized absorption and impacts cloud microphysics
- During first ORACLES mission, GEOS-5 model smoke plume was systematically lower than HSRL-2 observations (da Silva - GSFC)

HSRL-2 Aerosol Backscatter (532 nm)



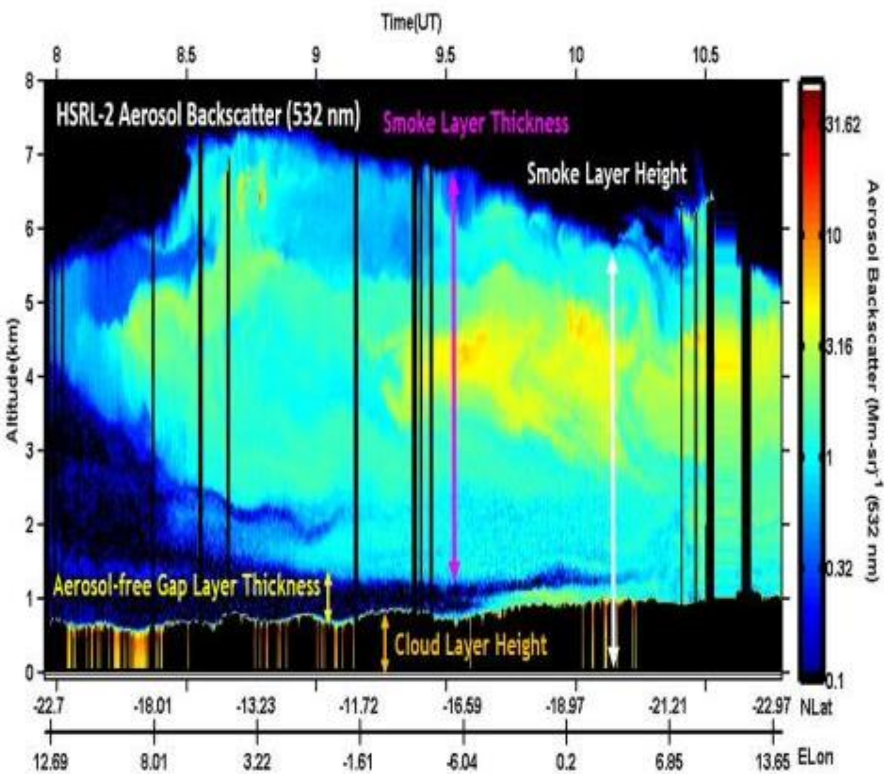


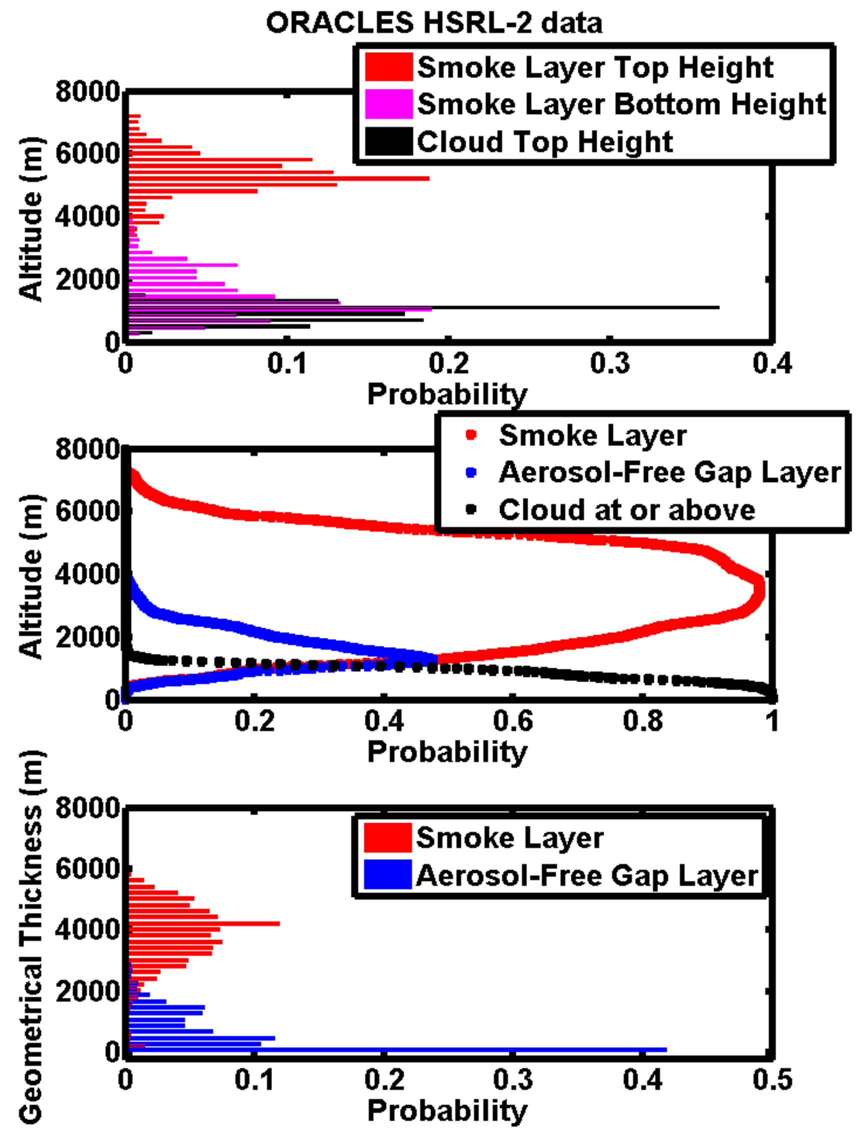




HSRL-2 characterization of smoke layer

- HSRL-2 aerosol backscatter measurements characterize:
  - smoke and cloud layer heights and thicknesses
  - thickness of the aerosol-free layer between the smoke and cloud layers (i.e. the "gap")
- Much (>40%) of the time, there is no gap

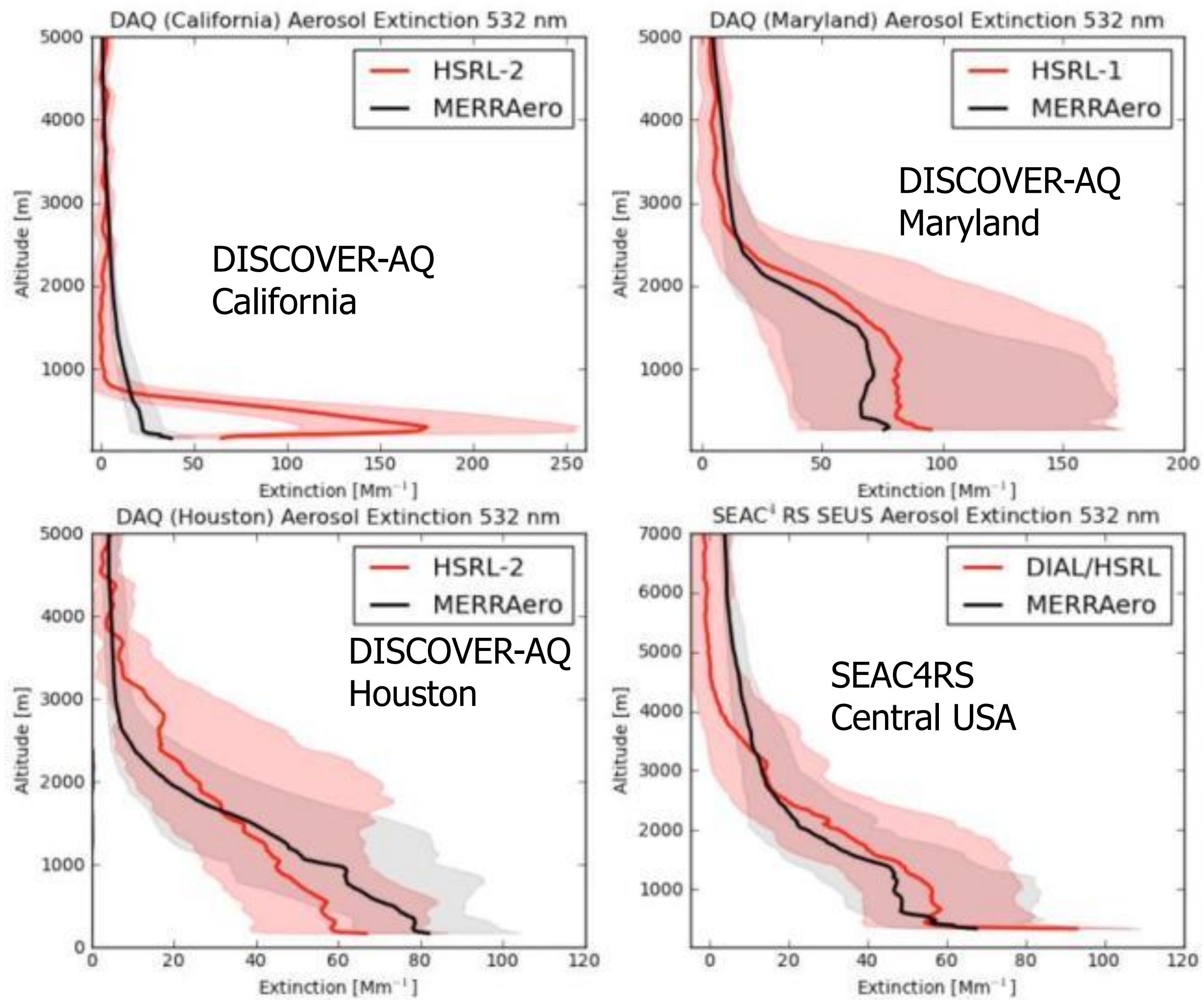




Assessing Aerosol Data Assimilation Products Using HSRL Measurements

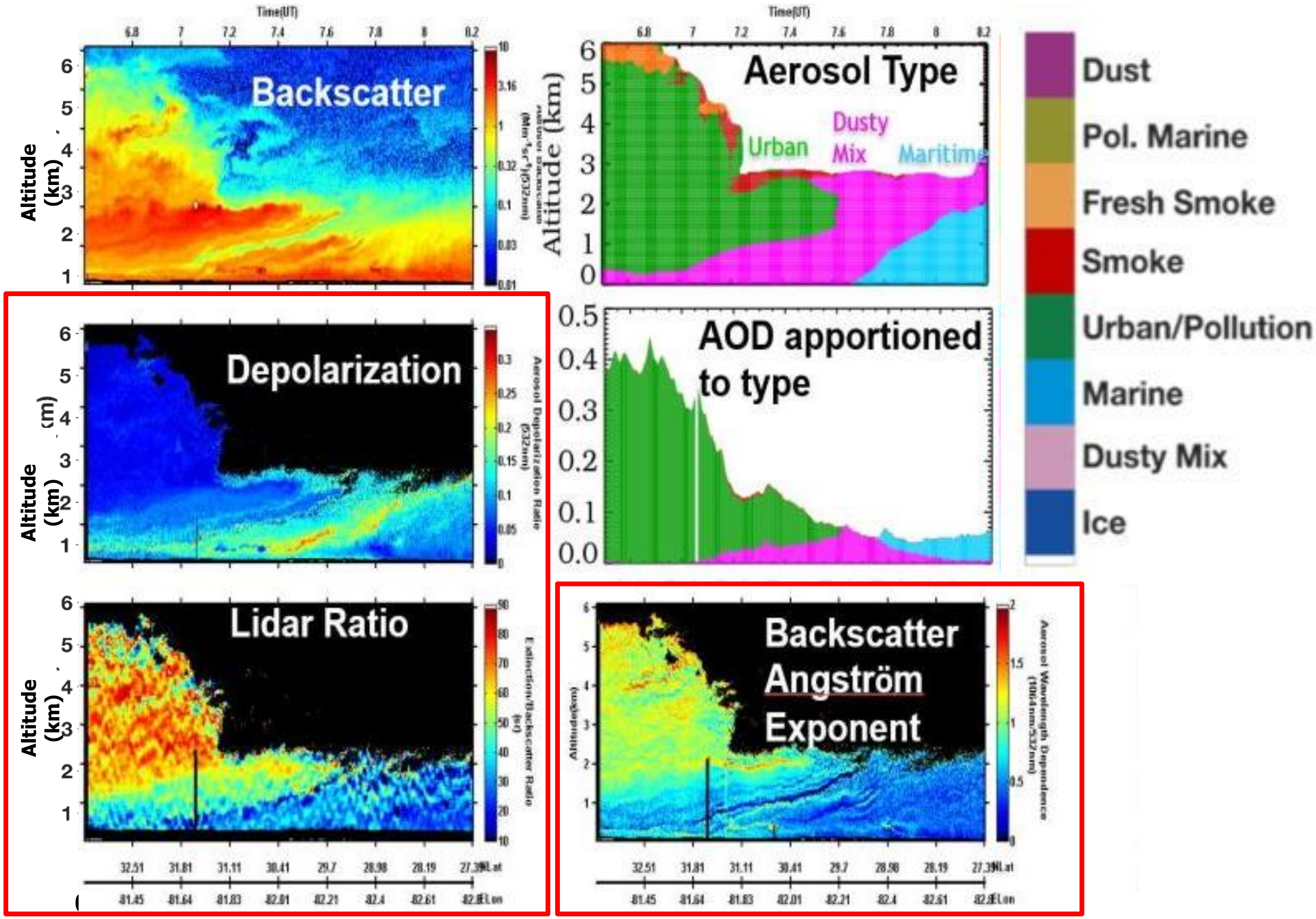
- HSRL aerosol extinction profiles are being used to assess and improve aerosol data assimilation systems (NASA GEOS-5 and MERRAero, ECMWF/MACC-III)
- With exception of California San Joaquin Valley, MERRAero mean aerosol extinction profiles are in general agreement with HSRL

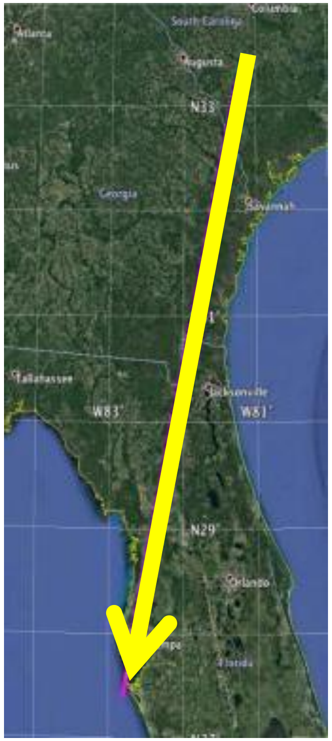
Mean Aerosol Extinction Profiles



Buchard et al., 2015, Atmos. Environ.

HSRL technique enables identification of aerosol type and apportioning optical depth by type





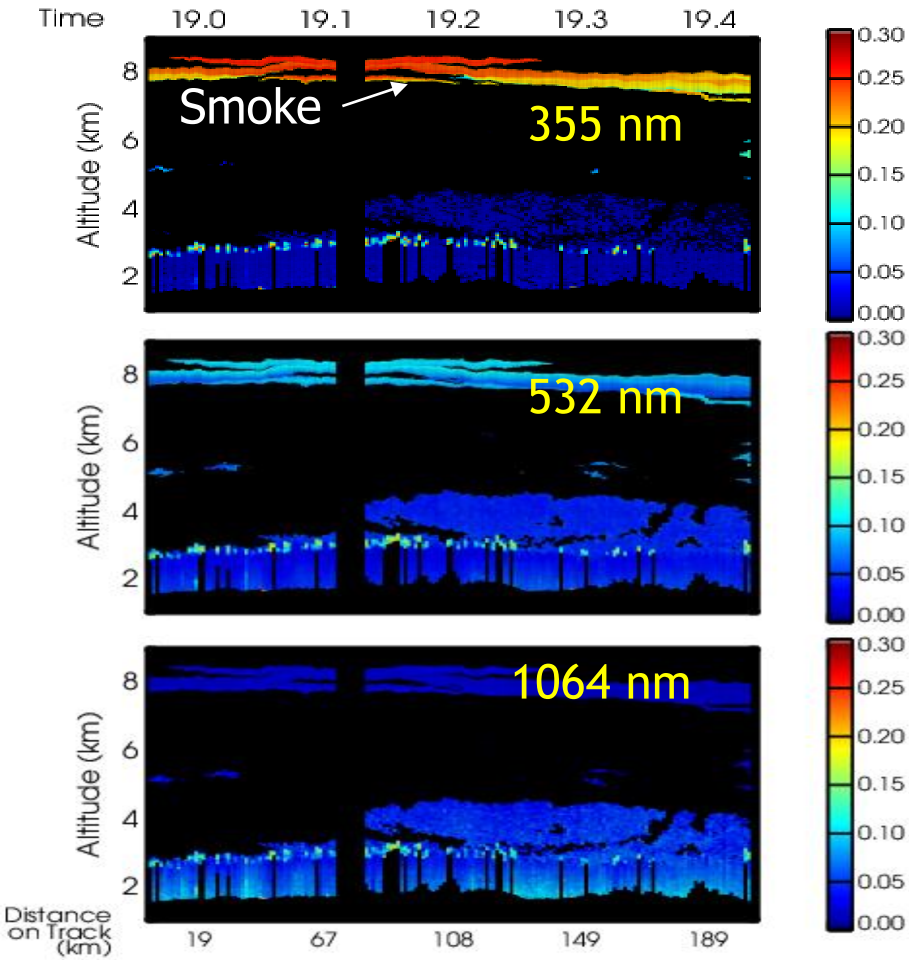
Intensive observables:

- Independent of aerosol amount
- Depends only on aerosol type

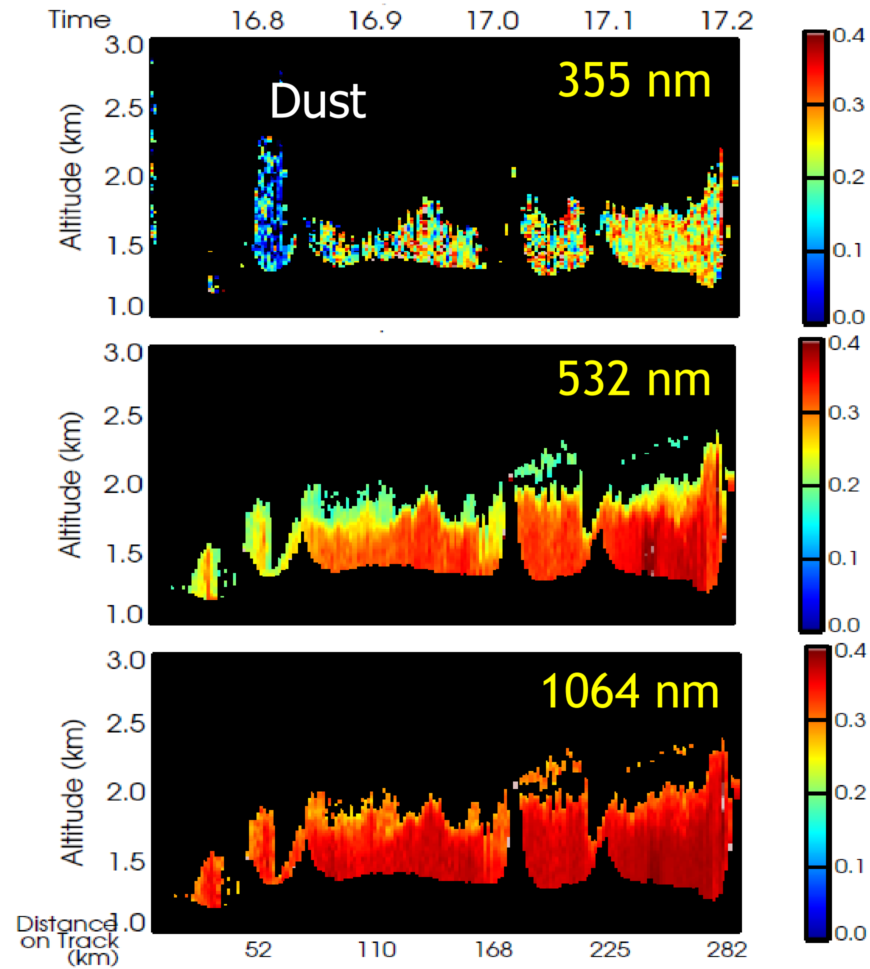
Burton et al., 2012, AMT

Spectral dependence of particle depolarization differs for smoke and dust

Smoke depolarization decreases with wavelength

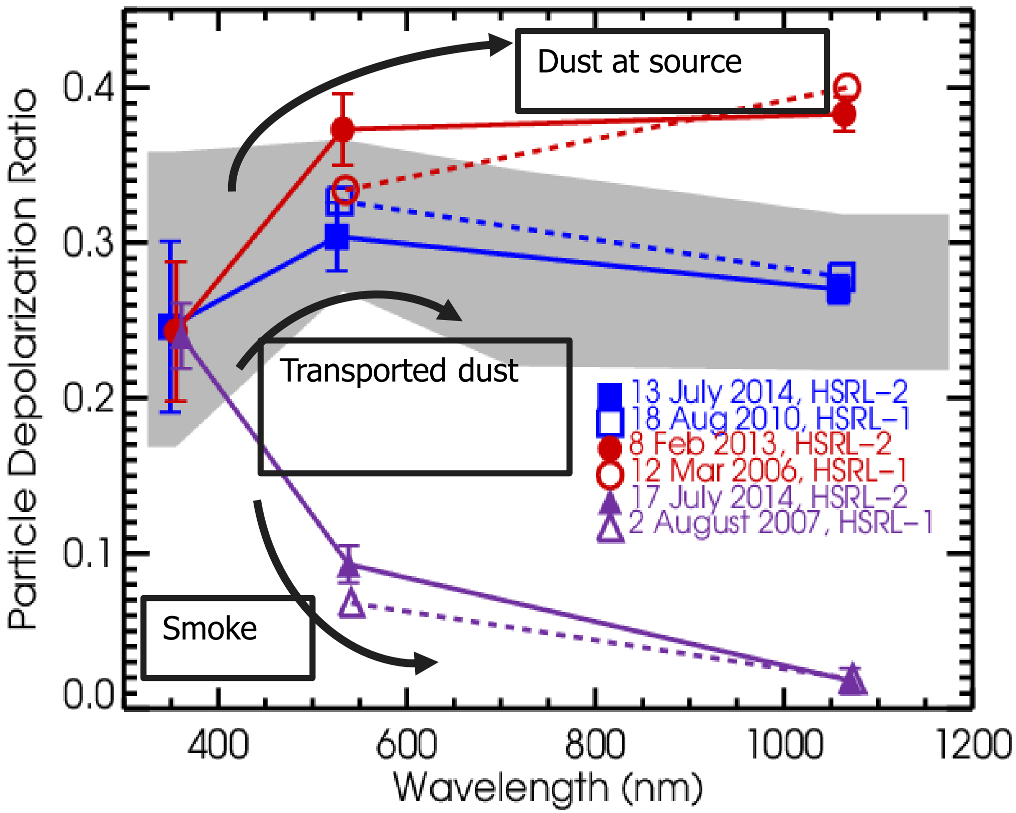


Dust depolarization increases with wavelength



Burton et al. ACP 2015

Spectral depolarization reveals information about particle size distribution

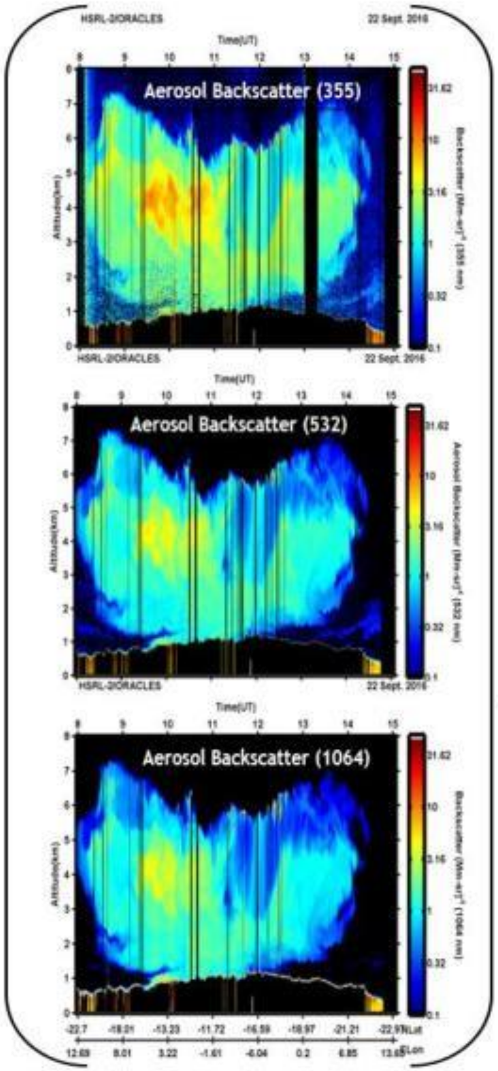


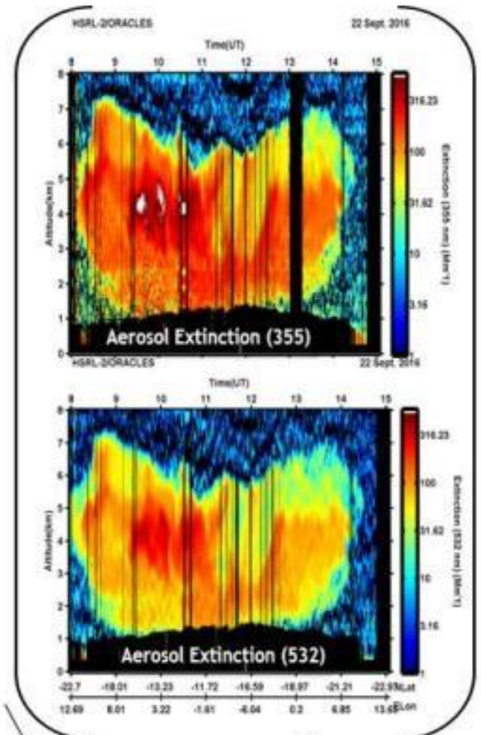
3 case studies from HSRL-2 (3 wavelength) + 3 from HSRL-1 (2 wavelength)

Burton et al., ACP, 2015

- Wavelength dependence of particle depolarization reveals information about particle size
- North American dust at the source includes very large particles, monotonically increasing depolarization
- Transported Saharan dust cases peak at mid-wavelength, largest particles were lost during transport
- Non-spherical smoke particles (coated soot aggregates) have decreasing wavelength dependence, smaller particles
- 355 nm particulate depolarization alone (ATLID) not sufficient for separating dust and smoke

Multiwavelength HSRL-2 retrievals characterize aerosol concentration and size during ORACLES





Aerosol Backscatter:
355 nm
532 nm
1064 nm

+

Aerosol Extinction:
355 nm
532 nm

Input (Preliminary)

Multiwavelength lidar retrieval algorithms (Müller et al, 1999; Veselovskii et al. 2002; etc)

lidar measurements

particle size distribution

INVERSION

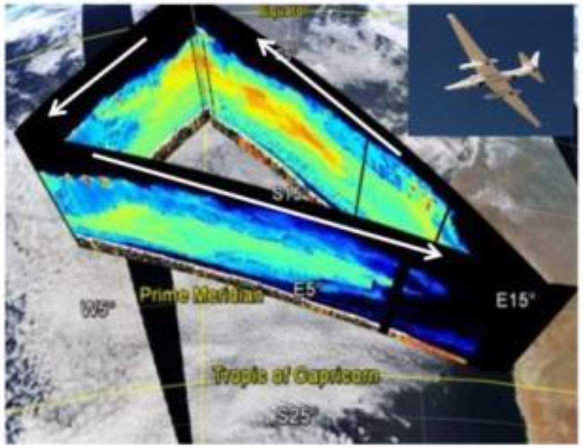
$$\beta(\lambda) = \int K_\beta(r, m, \lambda) v(r) dr$$

$$\alpha(\lambda) = \int K_\alpha(r, m, \lambda) v(r) dr$$

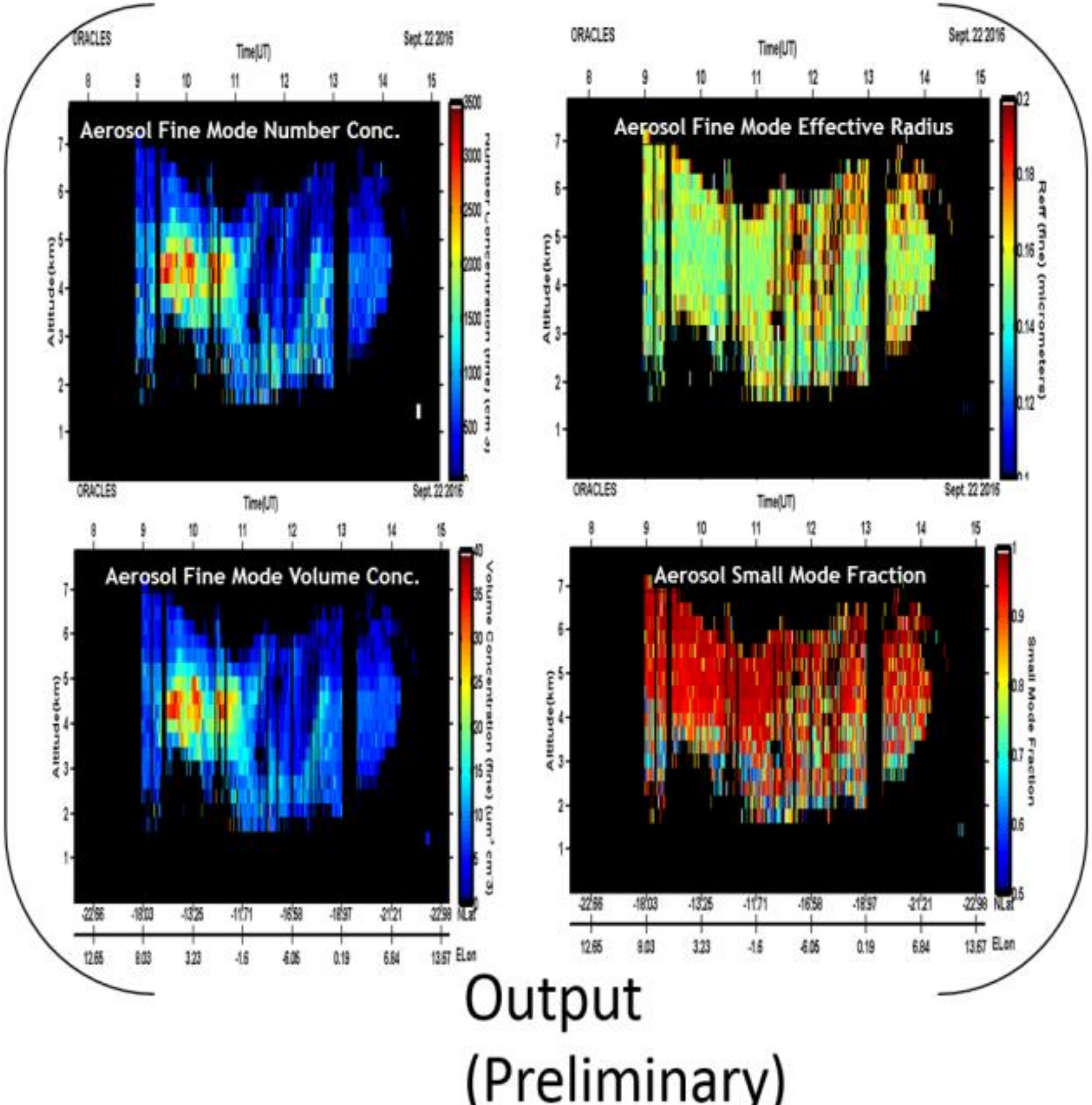
size, refractive index, wavelength

3β+2α (i.e. 3 backscatter + 2 extinction) considered the minimum information content necessary for microphysical retrievals (*Bockmann et al*, 2005)

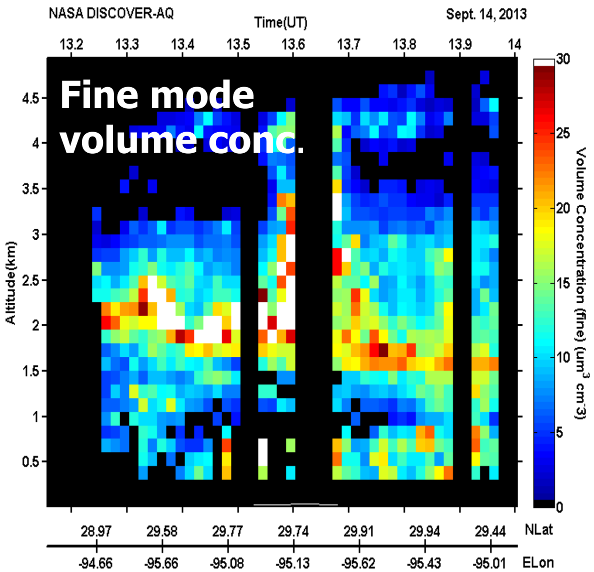
Multiwavelength HSRL-2 retrievals characterize aerosol concentration and size during ORACLES

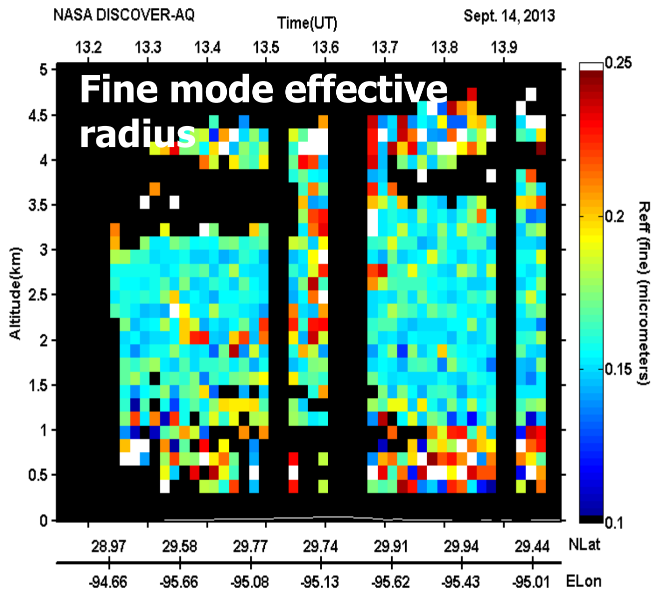


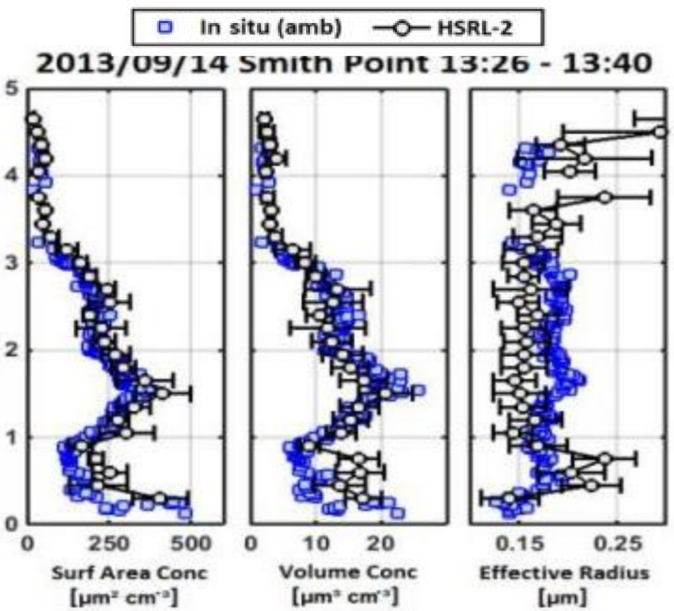
- Microphysical parameters retrieved and archived:
  - Concentration (fine and total) (number, surface, volume)
  - Effective radius (fine and total)
  - Small mode fraction



Multiwavelength HSRL aerosol retrieval profiles compare well to coincident airborne in situ measurements







Lidar microphysical retrievals of effective radius and concentrations compare well to airborne in situ measurements

- Relevance of particle size:
  - Improve parameterizations in aerosol transport models
  - Modeling direct radiative effects
  - Indirect effect on cloud radiative properties and precipitation (CCN)
- Relevance of particle concentration:
  - Indirect effects (CCN)
  - Air quality ($PM_{2.5}$)

Müller et al., 2014, AMT; Sawamura et al., 2017, ACP

Pursuing combined lidar+polarimeter retrievals

- Limits in information content for lidar-only microphysical retrieval means absorption is retrieved less well than size distribution parameters
- Synergistic combination of active (lidar) and passive (polarimeter) measurements will optimize information content on vertical profile of absorption properties

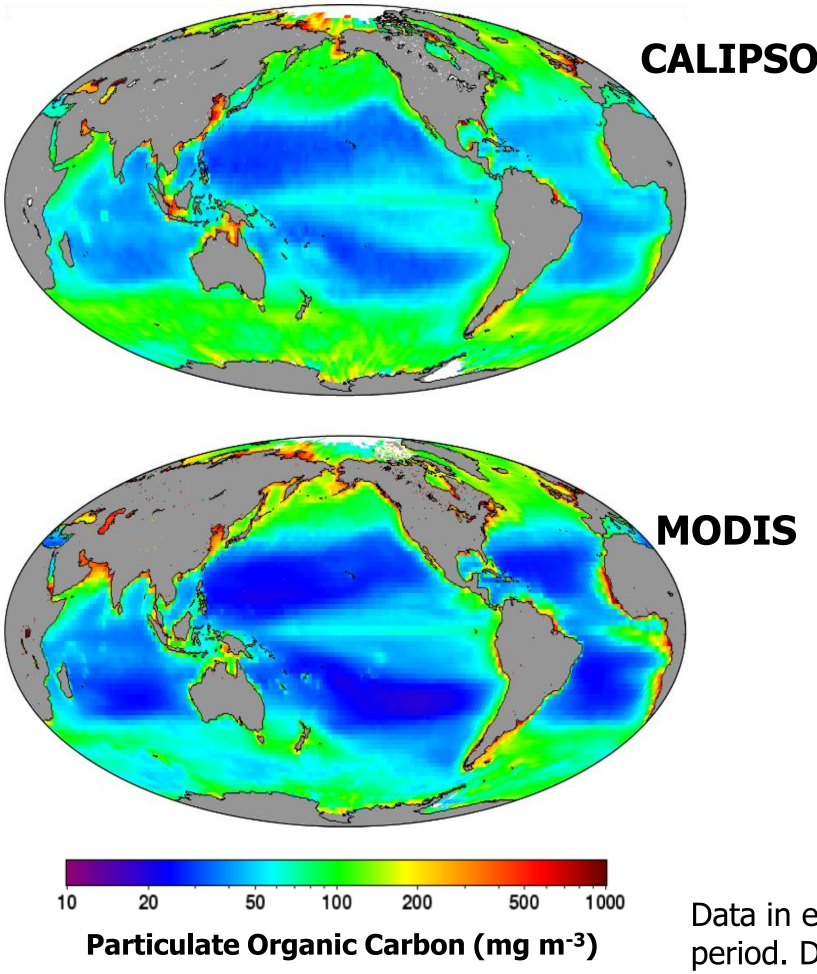
Lidar
- vertically resolved measurements
- multi-wavelength backscatter and extinction coefficients
- good accuracy for size distribution
- less accuracy for absorption

Polarimeter
- multiwavelength, multiangle
- polarized radiances
- good accuracy for absorption (e.g. ±0.02 on SSA)
- limited information on vertical profile

Lidar + Polarimeter
- vertically resolved profiles of effective radius, concentrations and complex refractive index

- Ongoing project by Xu Liu et al (NASA Langley) to combine HSRL-2 (lidar) and RSP (polarimeter) measurements in advanced Optimal Estimation retrieval

The unexpected application: CALIPSO ocean measurements



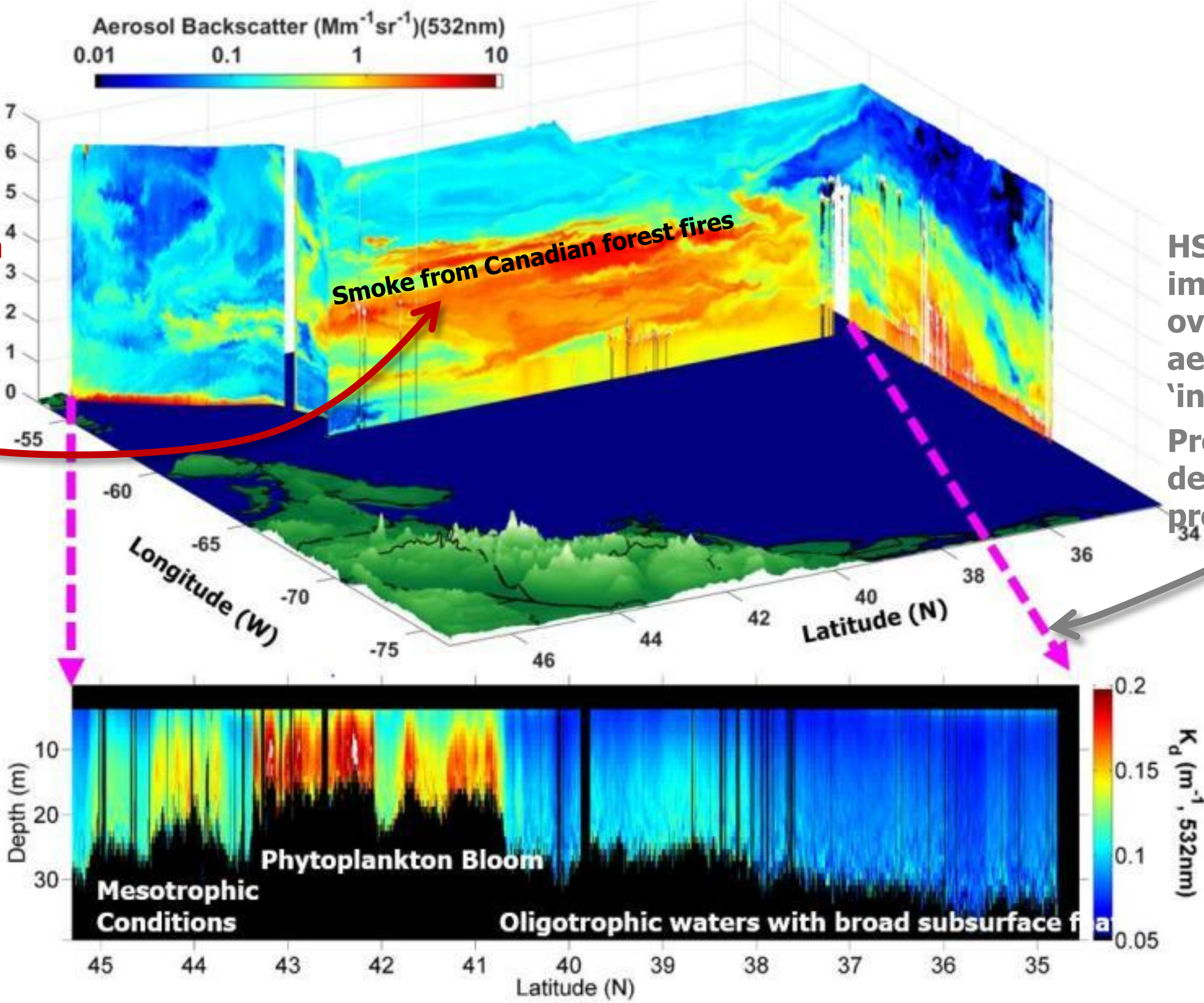
- Particulate Organic Carbon (POC) retrieved from CALIOP spaceborne lidar compared favorably to the MODIS product
- CALIOP retrievals pioneered by Yongxiang Hu
- CALIOP retrievals are vertically-integrated (i.e., not vertically-resolved) due to coarse vertical resolution

From supplementary material for: Behrenfeld et al., Space-based lidar measurements of global ocean carbon stocks, GRL, 2013.

Data in each panel are climatological annual averages for the 2006 to 2012 period. Data are binned to 2° latitude by 2° longitude pixels.

HSRL-1 Measurements of Atmospheric and Oceanic Particulates

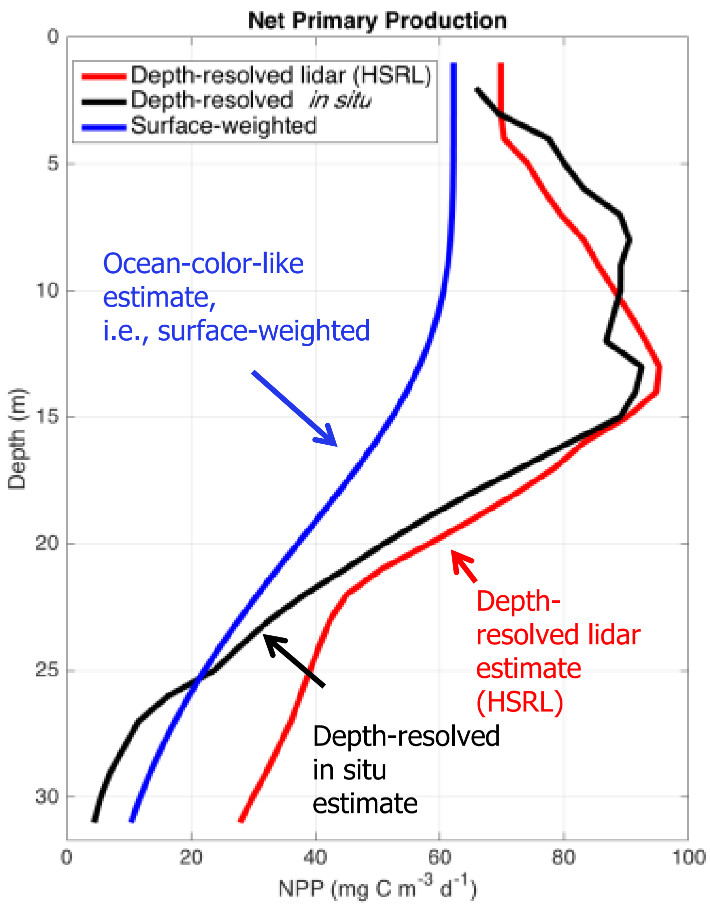
Dense smoke layers make passive 'ocean color' retrievals impossible



HSRL retrieval immune to overlying aerosol 'interference'.

Provides depth-resolved profile

Why do we care about depth-resolved profiles?



Modified from Schulien et al., **Vertically- resolved phytoplankton carbon and net primary production from a High Spectral Resolution Lidar**, submitted March 2017.

Net Primary Productivity (NPP)

- NPP = rate at which CO_2 is converted to biomass via photosynthesis
- Phytoplankton fix as much carbon as all the world's terrestrial vegetation – an critical component of the carbon cycle
- Phytoplankton are the base of the food web

Problem: ocean color measurements are sensitive to only the first few meters of the column

- Assumption of vertical homogeneity required to estimate ecosystem properties from ocean color data
- But, this assumption is often violated
- Results in large errors in fundamental quantities such as NPP

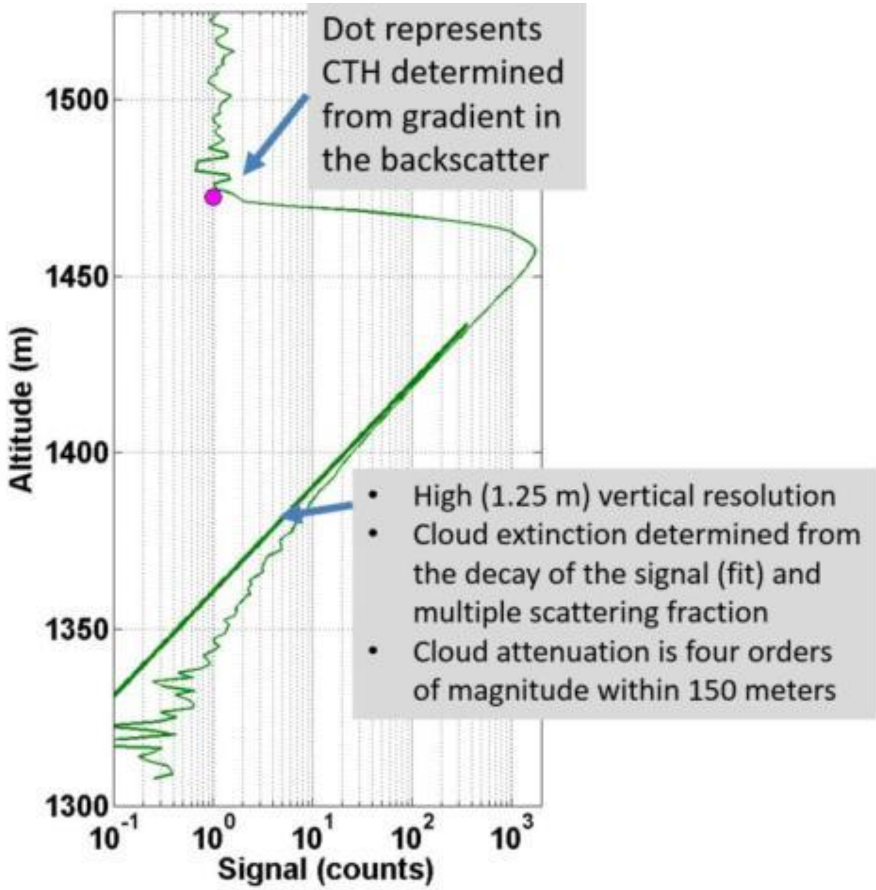
At left are data from the SABOR mission off East Coast US (2014) demonstrating differences between surface-weighted and depth resolved profiles using in situ and HSRL lidar data.

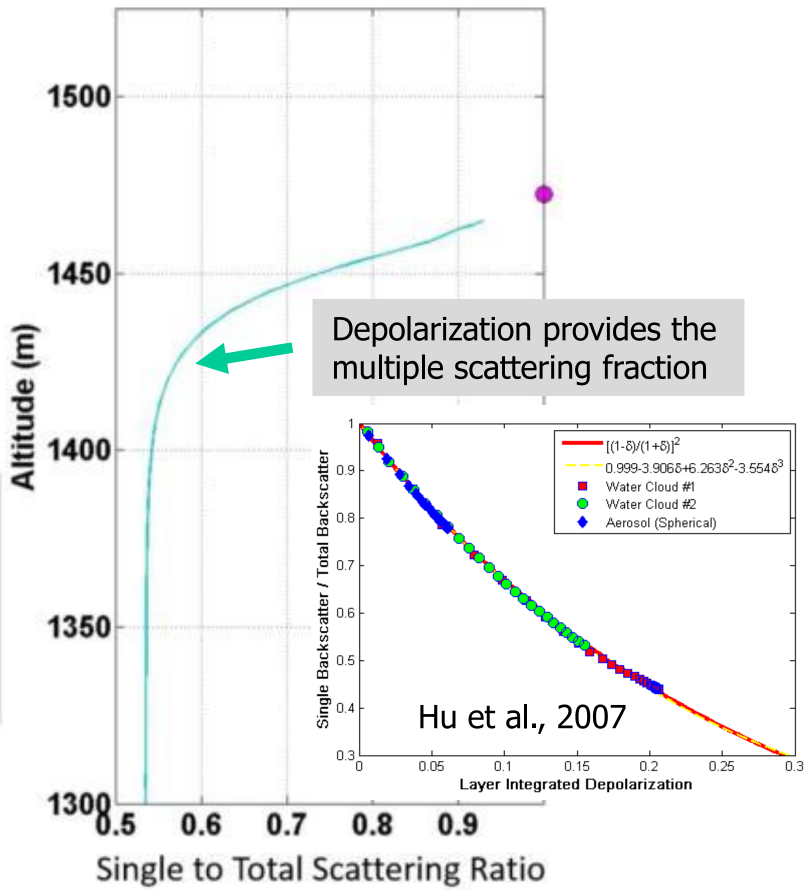
- Ocean-color-style estimates off by as much as 54%
- Errors can be much larger in other parts of the ocean

High vertical resolution also greatly facilitates water cloud extinction from LaRC airborne HSRL-1

- Fast, linear detector provides high vertical resolution (1.25 m) cloud extinction profile
- Cloud top height measured with high accuracy
- Depolarization provides multiple scattering fraction
- HSRL provides accurate measure of optical depth (i.e. attenuation) to cloud top

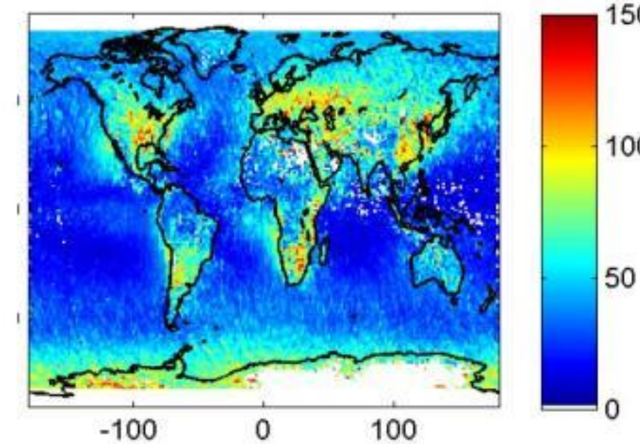
Example from HSRL-1 data from NAAMES mission





Cloud Drop Number Concentration (N_d) from Combined HSRL and Polarimeter Cloud Measurements

- CDNC derived from CALIPSO-MODIS-CERES (Hu et al., 2007)
  - CALIPSO cloud extinction retrievals
  - CERES-MODIS effective radius

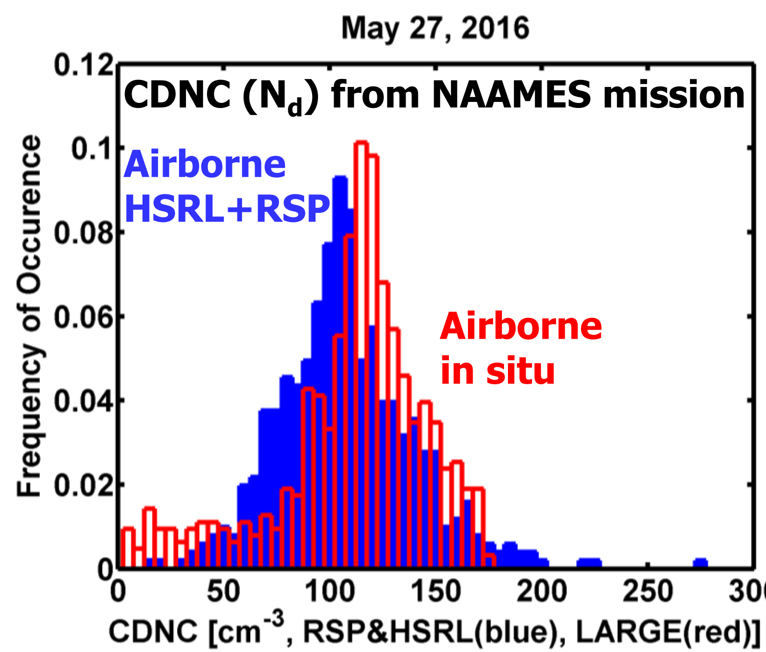


- Advantage of HSRL, Polarimeter retrievals
  - High resolution HSRL (active) - provides more accurate cloud extinction profile
  - RSP (passive) - provides more accurate cloud drop effective radius, variance

$$N_d = \frac{Extinction}{Scattering\ Cross\ Section}$$

From HSRL extinction retrieval with multiple scattering correction

From RSP size distributions



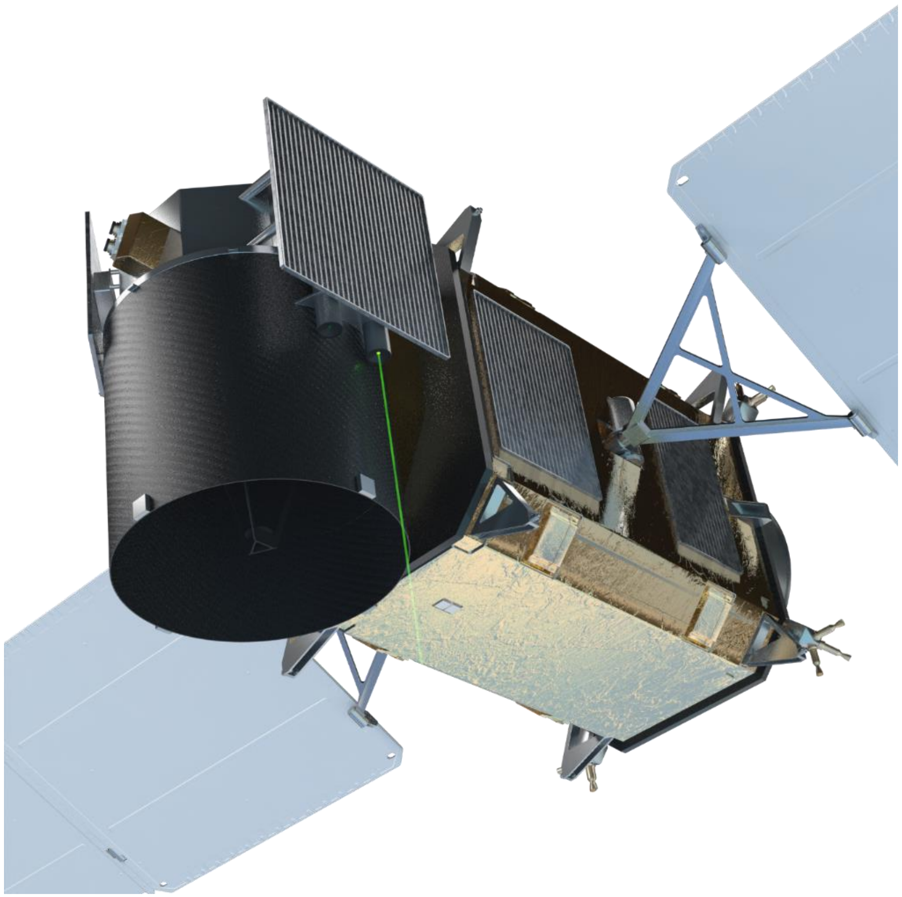
MESCAL:
Monitoring the Evolving State of Clouds and Aerosol Layers

- Began as a French cloud-aerosol focused lidar mission concept championed by Dr. Helene Chepfer (LMD/IPSL, Université Pierre et Marie Curie)

- Evolved into a joint mission study between CNES and NASA Langley

- Science requirements include
  - Continuation of CALIPSO cloud and aerosol record for radiation budget and cloud-climate feedback studies
  - Aerosol requirements from the ACE Decadal Survey mission (ACE = Aerosols-Cloud-Ecosystems mission)
  - Ocean requirements from ACE

- Langley concept based on CALIPSO and airborne HSRL heritage



Extra

Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO)

Objective: global profiling of clouds and aerosols for radiation budget applications

- 11 years of operations in the A-train constellation
- 1800 journal publications

Demonstrated

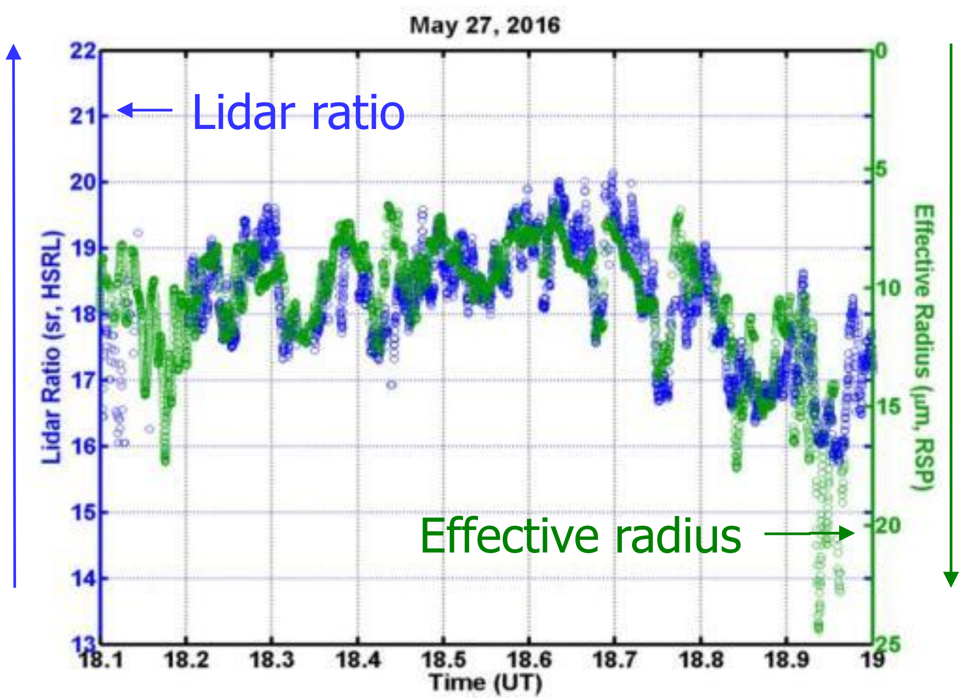
1. Necessity of vertically-resolved measurements for cloud and aerosol studies
2. That lidar can be reliable in space
3. Spaceborne lidar has the sensitivity to provide valuable ocean measurements

CALIPSO website: www-calipso.larc.nasa.gov

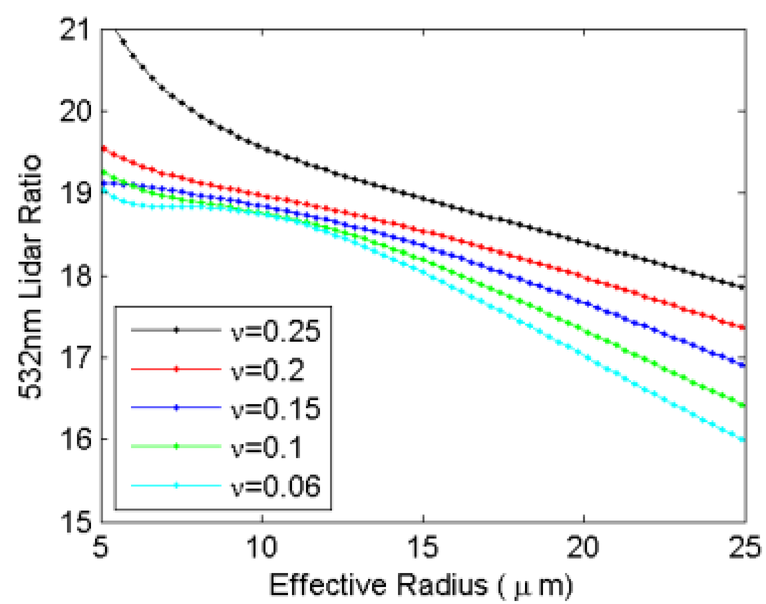
Cloud Drop Size from LaRC airborne HSRL-1

- Cloud lidar ratio (i.e. extinction/backscatter) is function of cloud drop size
- HSRL provides direct measure of cloud lidar ratio
- Initial comparisons of HSRL-1 derived cloud lidar ratio are well correlated with cloud drop effective radius derived from coincident RSP polarized radiance measurements

HSRL-1 and RSP measurements



Theoretical relationship



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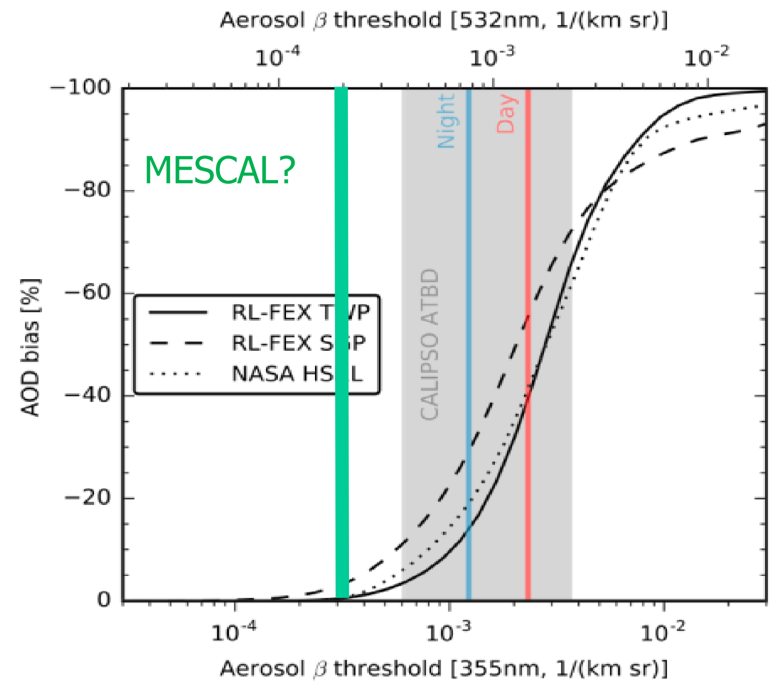
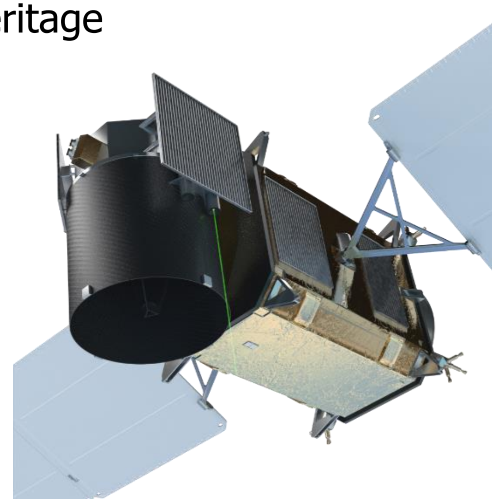
  - Ocean requirements from ACE
- Langley concept based on CALIPSO and airborne HSRL heritage



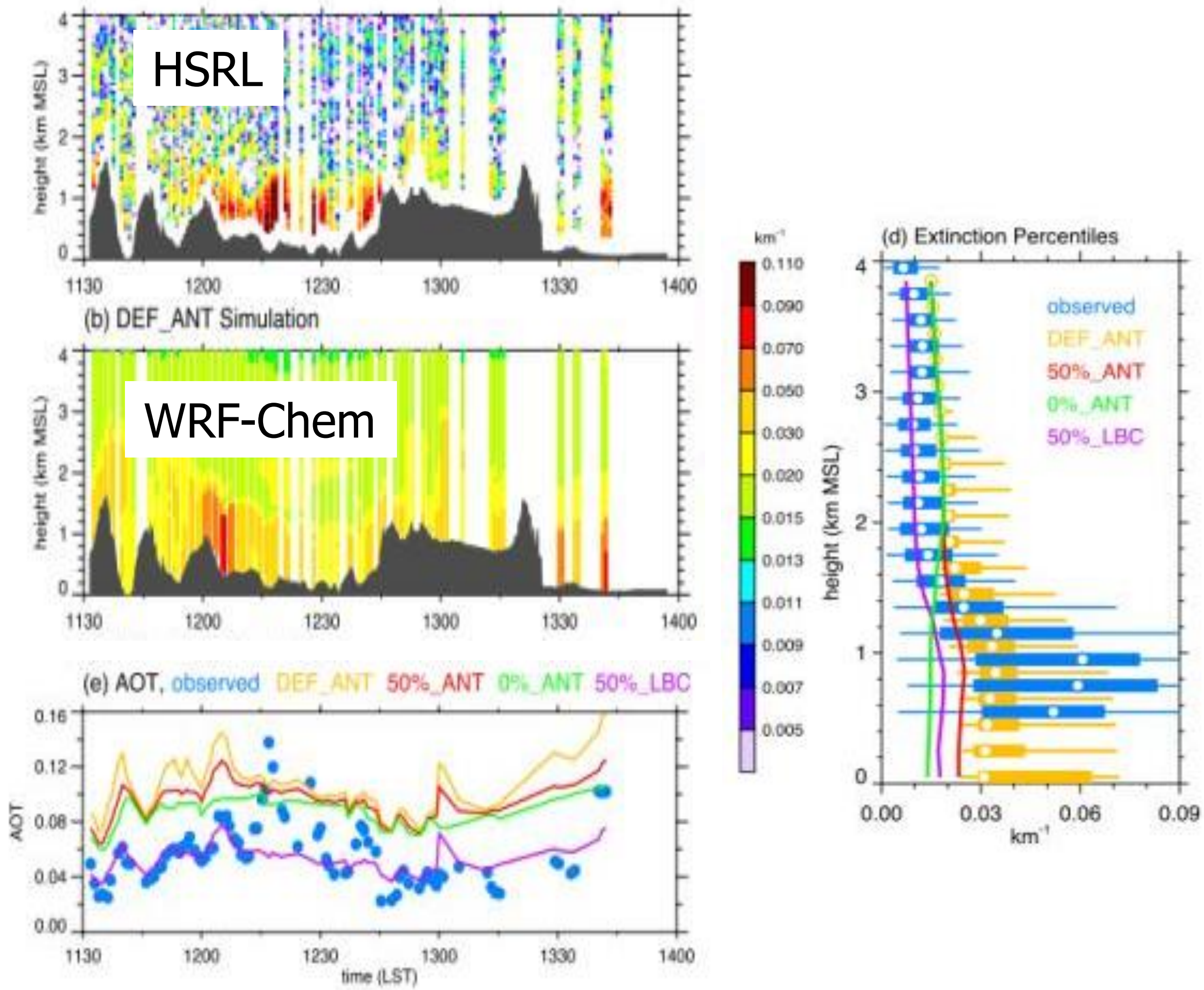


MESCAL raises possibilities:

- Reduce AOD bias, even during daytime
- Direct measurements of backscatter and extinction facilitates additional averaging or integration
- Multiwavelength HSRL techniques provide potential for retrieving additional parameters for radiative flux calculations and estimating aerosol forcing

HSRL measurements used to evaluate WRF Chem aerosol simulations

- WRF-Chem aerosol simulations from over California evaluated using HSRL
- HSRL was most valuable instrument to quantify overprediction of aerosols in free troposphere
- Long-range transport of aerosols by global model was too high in free troposphere. This bias led to overpredictions in AOD by factor of two and offsets effects of underprediction of BL aerosols
- Reducing long-range transport greatly improves simulated AOD



Fast et al., 2012, 2014, ACP